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13. ABSTRACT (Maximum 200 words) This is the final technical report on a three-year program of research on the microstructural and continuum mechanics of granular media and geomaterials initiated under the AFOSR Particulate Mechanics Program. The research has led to the development of new theoretical models of microstructure, numerical simulation of granular assemblages, and development of new experimental techniques. The overall goal of the work is to provide a sound microstructural basis for understanding continuum behavior and elucidating structurally and geologically important processes such as the propagation of acoustic and seismic waves, the quasi-static yield of granular media, the structural stability of soils and the non-invasive testing of geomaterials. The research effort has been mainly devoted to the mechanics of dense suspensions and granular media in the quasi-static flow regime, with emphasis on shearing and dilatational instabilities. A summary is given immediately below of accomplishments and plans for continuing efforts.			
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Final Technical Report

for the period

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on

AFOSR Research Grant F49620-96-1-0246

**QUASISTATIC MECHANICS
AND MATERIAL STABILITY OF PARTICULATE MEDIA**

Submitted to

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17 March 1999

SUMMARY OF OVERALL RESEARCH EFFORT

This is the final technical report on a three-year program of research on the microstructural and continuum mechanics of granular media and geomaterials initiated under the AFOSR Particulate Mechanics Program. The research has led to the development of new theoretical models of microstructure, numerical simulation of granular assemblages, and development of new experimental techniques. The overall goal of the work is to provide a sound microstructural basis for understanding continuum behavior and elucidating structurally and geologically important processes such as the propagation of acoustic and seismic waves, the quasi-static yield of granular media, the structural stability of soils and the non-invasive testing of geomaterials. The research effort has been mainly devoted to the mechanics of dense suspensions and granular media in the quasi-static flow regime, with emphasis on shearing and dilatational instabilities. A summary is given immediately below of accomplishments and plans for continuing efforts.

ACCOMPLISHMENTS AND FUTURE PLANS

A summary is given here according to tasks set forth in the original research proposal and amended in various progress reports to the AFOSR.

1. Numerical simulations of frictional sphere assemblies

A quasi-static (DEM) computer simulation, developed largely under a prior AFOSR grant, has been employed to simulate the mechanical behavior of rigid frictional sphere assemblies as a guide to the development of continuum models of granular dilatancy and plasticity. This work, the subject of several major journal publications and conference proceedings [1,2,35,12], has led to the confirmation of a new theoretical estimates of dilatancy, as an improvement on the classical Reynolds theory, and to a new statistical mechanical model of quasi-static granular flow, discussed below under Item 4.

2. Development of a photochromic tracer technique for particulate systems

As an effort launched under a companion AFOSR/AASERT grant, work has progressed significantly on the development of refractive-index matched fluid-particle systems, with transparent particles made from photochromic materials.

Initial attempts to impregnate commercially available acrylic beads with an organic photochromic dye (a spiropyran) were not successful, suggesting that synthesis of dye-containing beads may be necessary. Subsequent efforts were devoted to the use of photochromic glass. We have been able to synthesize a highly transparent "photochromic sand" consisting of crushed photochromic glass (provided by the Corning Company) in aqueous ZnCl solutions.

After repeated failures to generate dye streaks in completely photochromic glass by means of a pulsed Hg-Xenon UV lamp, we have finally found a successful method, based on using a dilute dispersion of photochromic in ordinary crushed glass, with a UV laser as illumination source. (The latter was made available to us by the manufacturer for purposes of this test.)

The work accomplished to date will serve as the basis of a new research proposal aimed at direct in situ observation of strain-induced liquefaction and shear banding in saturated granular media by means of the above photochromic tracer technique.

3. Theories of material stability in particulate systems

In conjunction with the AFOSR research, the P.I. has undertaken the theoretical study of shear banding instabilities in fluid-particle suspensions, which has led to several publications [4,8,9]. Included is a major

review article [4], co-authored with the newest member of our research group, Dr. M. Alam, which provides a unified treatment of material instabilities in quasi-static and rapid granular flows.

4. Micromechanical modelling

In conjunction with the above DEM simulation, an effort has been made to develop a continuum model for granular media based on a simplified statistical-mechanical model. In this model, particle motion is described via a stochastic diffusional motion superimposed on a globally applied strain. The numerical simulations show the diffusional motion to be relatively small, which among other things leads to a semi-theoretical microstructural ("fabric") evolution equations for granular assemblies [].

One member of our group has been involved in related research efforts on the mechanics of saturated granular materials and porous media, from which two papers [7,10] and a number of conference presentations have resulted.

5. Elastoplastic arching, and miscellaneous

This began as a sideline effort aimed at clearing up certain theoretical issues that have arisen in the recent physics literature on anomalous pressure distributions under granular heaps. In several conference papers and presentations [6,11], we have shown that such effects can be explained by via elastoplastic analyses. The specific novelty of our work is this the introduction of elastoplastic transitions, which have largely been ignored in all past treatments, classical as well as modern. A major journal paper is in progress which will cover both 2D wedges and axisymmetric heaps.

PUBLICATIONS AND PRESENTATIONS¹

Refereed Journals:

- 1.* Didwania, A.K. and Goddard, J.D. "Computations of Dilatancy and Yield Surfaces for Assemblies of Frictional Spheres", *Q. J. Mech. and Appl. Math.*, **51**, 15-43, 1997.
- 2.*Goddard, J.D. and Ledniczky, K. "On the Spectral Representation of Stretch and Rotation " *J. Elasticity* **47**, 255-259, 1997.
- 3.* Goddard, J.D. "Granular Dilatancy and the Plasticity of Glassy Lubricants", *Ind. & Eng. Chem. Research* (Special Issue Honoring Prof. Roy Jackson), **38**, 820-822, 1999.
- 4.*Goddard, J.D., and Alam, M., "Shear-Flow and Material Instabilities in Particulate Suspensions and Granular Media", *J. Particulate Tech.*, in the press, 1999.

Pending:

5. *Didwania, A.K., Ledniczky, K., and Goddard, J.D., "Particle Diffusion in Quasi-static Granular Flow", submitted to *J. Mech. Phys. Solids*, September, 1998, withdrawn at authors' request (because of lack of progress on review), revised and resubmitted as "Kinematic Diffusion in Quasi-static Granular Flow", to *Proc. Royal Soc. London A*, March 4, 1999.

Book Chapters and Refereed Conference Papers

- 6.* Cantelaube, F. and Goddard, J.D., "Elastoplastic Arching in 2d Granular Heaps", in

¹ Articles with asterisks include explicit acknowledgement of partial support from the current AFOSR grant.

Powders and Grains '9 , R. P. Behringer and J.T. Jenkins (eds.), pp. 231-234, Balkema, 1997.

7.*de Boer, R. and Didwania, A. K., "The effect of uplift in liquid-saturated porous solids - Karl von Terzaghi's contributions and recent findings ", *Geotechnique* , **47**, 289-298 (1997).

8. Goddard, J.D., "Migrational Instability in Shear-Thinning Suspensions", in *Lubricated Transport of Viscous Materials* , Proc. IUTAM Symposium , Tobago, West Indies, 1997, H. Ramkisoorn et al. (eds.), pp. 193-196, Kluwer, 1997.

9. Goddard, J.D., "Migrational Instabilities in Particle Suspensions", in *Dynamics of Complex Fluids* , Proc. Royal Society-Unilever Indo/UK Forum, 1996 , M. Adams et al. (eds.), Imperial College Press - The Royal Society, Chapt. 19, pp. 281-286, 1998.

10.*Didwania, A. K. and de Boer, R., "Saturated Compressible and Incompressible Porous Solids: Macro- and Micromechanical Approaches", *Transport in Porous Media* **6**, 1-15 (1998).

11.*Cantelaube F., Didwania, A.K. and Goddard, J.D. "Elastoplastic Arching in Two-Dimensional Granular Heaps", in *Physics of Dry Granular Media* (Proc. NATO Advanced Study Institute ,Corsica, Sept. 1997,) H. Herrmann et al. (eds.), 3pp., Kluwer, 1998.

12,*Goddard, J.D., "Continuum Modeling of Granular Assemblies - Quasi-Static Dilatancy and Yield", Chapter in *Physics of Dry Granular Media*, (Proc. NATO Advanced Study Institute, Corsica, Sept. 15-26, 1997, H. Herrmann et al. (eds.), 24 pp., Kluwer, 1998.

*Conference Presentations and Invited Lectures

13. Goddard, J.D., "Migrational Instabilities in Sheared Particle Suspensions", Paper AC4, 49th Ann. APS/DFD mtg., Syracuse, NY, 24 November 1996.
14. _____ "Migrational Instabilities and Core-Annular Flow in Particle Suspension", International Symposium on Lubricated Transport of Viscous Materials, Tobago, Trinidad, West Indies, 7-10 January 1997.
15. Cantelaube, F., "Elastoplastic Arching in 2D Granular Heaps", Powders and Grains '97, Durham, NC, 17-23 May 1997.
16. Didwania, A. K., "Dry and Saturated Porous media: A micromechanical view", (Invited Keynote lecture), Euromech Colloquium No. 366, "Porous Media, Theory and Experiments.", 23-26 June, Essen, Germany, 1997
17. Cantelaube, F. "Elastoplastic Arching and Static Indeterminacy in 2D Granular Heaps", research paper, NATO Advanced Study Institute, "Physics of Dry Granular Media", Sept. 15-26,, 1997
18. Goddard, J.D., "Fabric, contact networks and granular statics", and "Estimates of dilatancy and yield surfaces for granular assemblies", NATO Advanced Study Institute, "Physics of Dry Granular Media", Cargese, Corsica, 15-26 September 1997.
19. _____ "Reynolds Dilatancy as Macro-Constraint", Conference on Jamming and Rheology, Institute for Theoretical Physics, UC Santa Barbara, October 12-16, 1997.
20. _____ "Quasi-static Statistical Mechanics and Plasticity of Rigid Sphere Assemblies", Paper HT6, Ann. Soc. of Rheology Mtg., Columbus, OH, 20 October 1997.
21. (2 papers) _____ "Elastoplastic Arching in 2D Granular Heaps", Paper HT4, Ann. Soc. of Rheology Mtg., Columbus, OH, 20 October 1997 and Paper PTP 2214, Particle Tech. Forum, Ann. Mtg. A.I.Ch.E., 16-21 November 1997, Los Angeles, CA, 1997
22. Goddard, J.D. "Computations of Dilatancy and Yield Surfaces for Frictional Sphere Assemblies", (Poster) PTP 2220, Solids Flow, Handling and Processing, Ann. Mtg. A.I.Ch.E., 16-21 November 1997, Los Angeles, CA, 1997
23. _____ "Migrational Instability in Particle Suspensions", Paper PTP 2678, Fund. Res. in Fluid Mech., Ann. Mtg. A.I.Ch.E., 16-21 November 1997, Los Angeles, CA, 1997.
24. Goddard, J.D. "Dilatancy and Yield in Sand and Grease - O! Reynolds, O! Reynolds", Graduate Seminar, Dept. of Mechanical and Environmental Engineering, UC Santa Barbara, December 1, 1997.
25. _____ "Elastoplasticity for Busy Professionals (or Uncritical-State Soil Mechanics)", Jamming and Rheology Seminar, Insstitute for Theoretical Physics, UC Santa Barbara, December 3, 1997.

26. _____ "Numerical Test of a Kinetic Theory for Slow Granular Flow", 12th ASME/EMD Conference, La Jolla, CA, 17-20 May, 1998.
27. Didwania, A. K., "The Effective Stress Principle and its extensions", 12th ASME/EMD Conference, La Jolla, CA, 17-20 May, 1998.
28. Goddard, J.D. "Reynolds Dilatancy-from the Gritty to the Glassy", Graduate Seminar, Department of Chemical Engineering, Princeton University, March 11, 1998.
29. _____ "Mechanics of Granular Media, with Worm's Eye View of Soil Mechanics", Exxon Research and Engineering, Annandale, NJ, March 12, 1998.
30. _____ "Elastoplastic Arching and Physics Built on Sand", Graduate Seminar, The Levich Institute, CCNY, NY, March 13, 1998
31. _____ "A Kinetic Theory for Slow Granular Flow", Theory Workshop on the Dynamics of Granular Materials, Argonne National Laboratory, April 16-18, 1998.
32. _____ "Statistical Mechanics of Quasi-Static Fabric Evolution in Granular Flows," Workshop on Granular Materials: Statics, Excitations and Dynamics, University of New Mexico, Center for Advanced Studies, Albuquerque, NM, June 25-26, 1998.
33. _____ "Material Instabilities in Particulate Systems" Paper 4B.3, 4th NASA Microgravity Fluid Physics Conference, Cleveland, OH, August 12-14, 1998.
34. _____ "Particle Migration Effects in Dense Suspensions and Granular Media", Paper 125b (Acrivos Birthday Symposium), Annual AIChE Mtg., Miami, FL, Nov. 18, 1998.
35. _____ "Reynolds Dilatancy and Material Instability in Dense Suspensions", Paper LD.08, Annual APS/DFD Mtg., Philadelphia, PA, Nov. 22-24, 1998.
- 36.(two talks) _____ "Shear-Flow and Material Instabilities in Granular Media and Dense Suspensions" SFB Colloquium,, Technical University of Darmstadt, Feb. 15-16, Seminar Ecole Polytechnique, Paris, Feb. 19, 1999.
37. _____ "Naïve Statistical Mechanics for Quasi-Static Granular Flow", DFG Symposium on Granular Materials, U.

Pending:

38. _____, and Alam, M., "Faraday Waves in Vibrated Granular Layers: A Fluid-Mechanical Model", SIAM Conference on Dynamical Systems, Snowbird, Utah, May 23-27, 1999
39. _____ "A Statistical Mechanical Model for Slow Granular Flow", IUTAM Symposium "Segregation in Granular Flows", Cape May, NJ, June 5-9, 1999.

40. *Alam, M. _____ "Relation of Layering Instabilities to Material Instability in Granular Shear Flows", ASCE Eng. Mech. Specialty Conf., Johns Hopkins University, Baltimore, MD, June 13-16, 1999.

41. _____, Invited Discussion Leader, Gordon Research Conference on Gravitational Effects in Physico-Chemical System/ Dynamics of Granular Materials", June 27-July 2, 1999.

PROFESSIONAL INTERACTIONS

Distinctions

Didwania, A. K., Invited keynote lecture, Euromech Colloquium No. 366, "Porous Media, Theory and Experiments.", 23-26 June, Essen, Germany, 1997.

Goddard, J.D., Invited researcher, in residence, Institute for Theoretical Physics Program "Jamming and Rheology: Constrained Dynamics on Microscopic and Macroscopic Scales", U.C. Santa Barbara, September-December 1997.

Goddard, J.D, Invited Lecturer, NATO Advanced Study Institute, "Phyics of Dry Granular Media", Cargese, Corsica, 15-26 September, 1997.

Professional Service, J.D. Goddard

Editorial Boards:

Non-Newtonian Fluid Mech. (continuing)

International J. Engineering Science (continuing)

Committees and Panels:

National Aeronautics and Space Administration:

Discipline Working Group, Fluid Physics 1992-

Chair, Microgravity Fluid Physics NRA Review Panel on Complex Fluids (including particulate media), 1997

American Physical Society:

Fluid Dynamics Prize Committee 1995-98

Fulbright Screening Committee, Engineering, 1997

Conference Organization and Chairmanship:

Sci. Program Committee, "Powders and Grains '97", 1995-97

Session Co-Chair, 67th Ann. Soc. of Rheology Mtg., Session on Heterogeneous Systems (Granular Media and Foams), Columbus, OH, October 19-26, 1997

UCSD Organizing Committee, 12th Eng. Mech. Div. Conf., ASCE, La Jolla, CA, 1997

PERSONNEL

In addition to the P.I. , the research has involved the following personnel in the University of California, San Diego (UCSD), with appointment dates at UCSD in parentheses:

Dr. Anjani Didwania, Research Scientist/ Scholar (1992-present)

Dr. Florence Cantelaube, Postdoctoral Resarch Engineer (1 August 1996 to 31 August 1997)

Ms. Elizabeth Kristofetz (Supported by companion AFOSR/ASSERT grant), Ph. D. Student, Materials Science and Engineering (01 March to 31 May 1997)

Ms. Klara Ledniczky ,Visiting Koranyi Scholar from the Technical University of Budapest (15 September 1996 to 30 June 1997)

Mr. Ben King, Undergraduate Laboratory Assistant (1 June 1996 to 31 December 1997)

Ms. Vanessa Le , Undergraduate Laboratory Assistant, UCSD Mc Nair Scholar
(01 January to 31 August 1997)

Ms. C. Tang, Undergraduate Laboratory Assistant (Summer 1998)

Mr. K. Roueiheb, M.S. Laboratory Assistant (Summer 1998.)

Dr. M. Alam, Postdoctoral Research Engineer (July 1998-present)